Hydraulic Model Studies of Aeration Enhancements at the Folsom Dam Outlet Works: Reducing Cavitation Damage Potential

by K. Warren Frizell
Research Hydraulic Engineer
Water Resources Research Laboratory

Introduction

Folsom Dam is on the American River about 20 miles northeast of Sacramento, California. The dam was built by the Corps of Engineers and transferred to Reclamation for operation and maintenance in 1956. The dam is a concrete gravity structure 340 ft high and impounds a reservoir of a little over one million acre-ft.

The dam features two tiers of four outlets each (figure 1), controlled by 5- by 9-ft slide gates. The outlets consist of rectangular conduits of formed concrete passing through the dam and exiting on the face of the

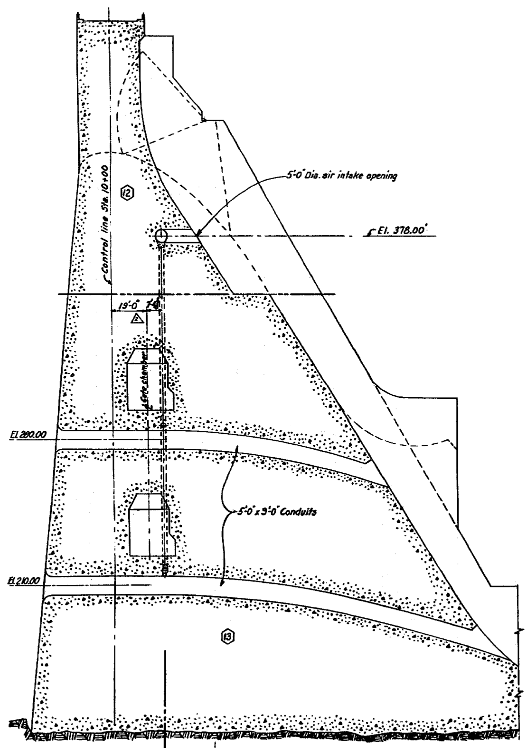


Figure 1: Section through the dam showing outlet works.

service spillway. Historically, the outlets have not been operated much. Flood releases in 1955, 1963, and 1964 resulted in cavitation damage initiating at the constriction on the crown of the outlets just upstream from the junction with the spillway face. The 1955 flood conditions were studied by the Corps using the model for Red Rock Dam which had a similar outlet configuration [USACE 1965]. These tests revealed scaled vapor pressure readings at several piezometer locations near where the damage had occurred.

Reclamation studied the problem using a 1:16.7 scale sectional model of one of the upper tier outlets [Isbester, 1971]. An eyebrow-type flow deflector was tested and later installed at Folsom over each outlet exit, figure 2. Besides the eyebrow, a gate operating restriction of 60-percent maximum was set when combining outlet works flows with spillway flows. These modifications to the structure and operating criteria have performed well over the years and no additional damage has occurred at the outlet/spillway junction.

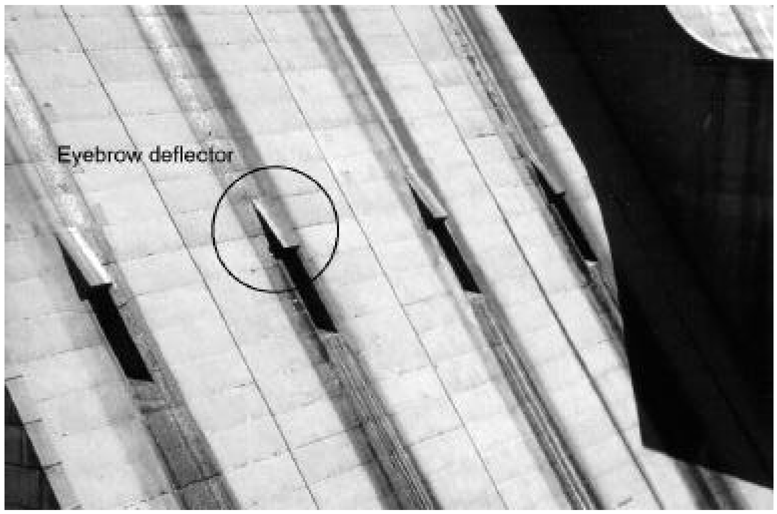
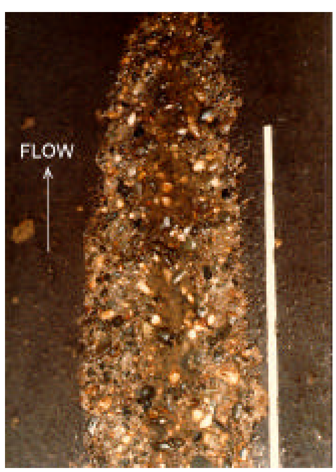


Figure 2: Eyebrow deflector installed above an outlet exit on the Folsom spillway.

Additional repairs to the outlet conduits (No.s 1-4) were completed in March of 1988. These repairs followed discovery of damage to the invert and lower sidewalls of the low-level outlets at locations from 15- to 60-ft downstream from the end of the gate frame, figure 3.



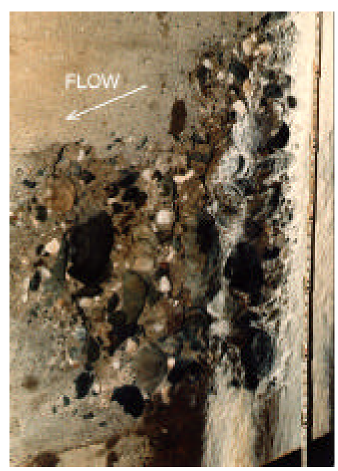


Figure 3: Damage to invert (left) and the sidewall (right) which occurred in 1987. This damage was 30 to 40 ft downstream from the end of the metal liner.

Operational records from 1988 to the present show increased operation of the low-level outlets at large gate openings since 1993. Between 40- and 45-percent of the total operation of the low-level outlets since that time has been at gate openings of 6 ft or greater (>67 percent open). This change in operations was due to revisions of the operation plan calling for more frequent use of the outlets in order to reduce the chance of exceeding levee capacity downstream and also to supplement flows during repair of the spillway gates.

During major releases in the winter of 1996/1997, observers noted that the trajectories of the discharge from outlets No. 3 and 4 were falling short of those from outlets No. 1 and 2. Inspections in May 1997 revealed major damage due to cavitation in outlets No. 3 and 4 (figure 4), minor damage in outlet No. 2 (figure 5) and little or no damage in Numbers 1, 5, 6, 7, and 8.

Figure 4: Damage to conduits 3 and 4, low-level outlets, May 1997.

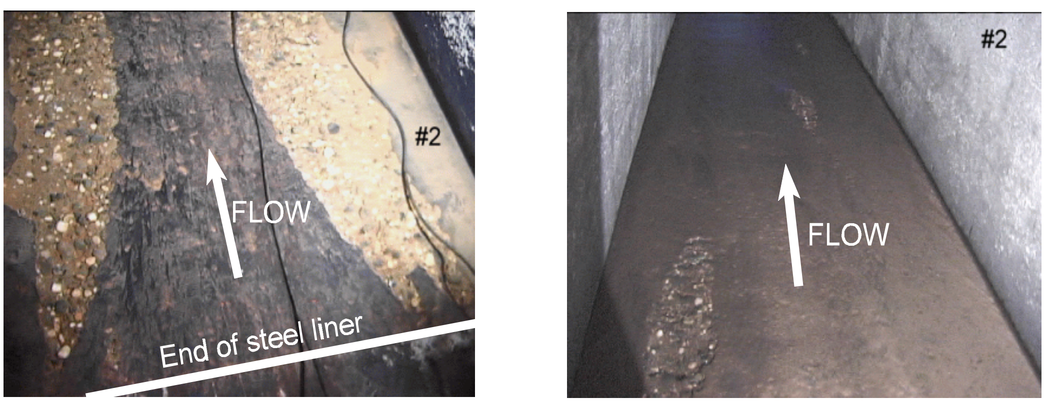


Figure 5: Damage to invert of conduit 2. Left photo is at the end of the steel liner. Note the pattern of damage on the right photo.

This damage was initiated by cavitation and accelerated by a combination of both cavitation and abrasion. Abrasion damage is probably primarily responsible for the deep lateral extent of the damage in outlets No. 3 and 4, especially along the construction joints. There was a widely varying degree of damage between outlets 1, 2, 3 and 4. Cavitation intensity is largely a function of pressure and velocity so the variation in damage is attributable to very low localized pressures downstream from the gates due to air starvation. Previous studies show the manifold system is undersized for the expected air demand. Outlets 3 and 4 are at the end of the air manifold that brings air to the conduits.

Model Studies

A 1:12 scale Froude-based hydraulic model of a single low-level outlet gate and conduit was constructed in Reclamation's Water Resources Research Lab. This model was used to verify present operating conditions as well as test modifications aimed at preventing future cavitation damage. The sectional model included the 5- by 9-ft slide gate and the rectangular conduit downstream from the gate. The junction between the outlet and the spillway was also modeled to allow observations of combined spillway and outlet works operations with any proposed modification to the structure, figure 6.

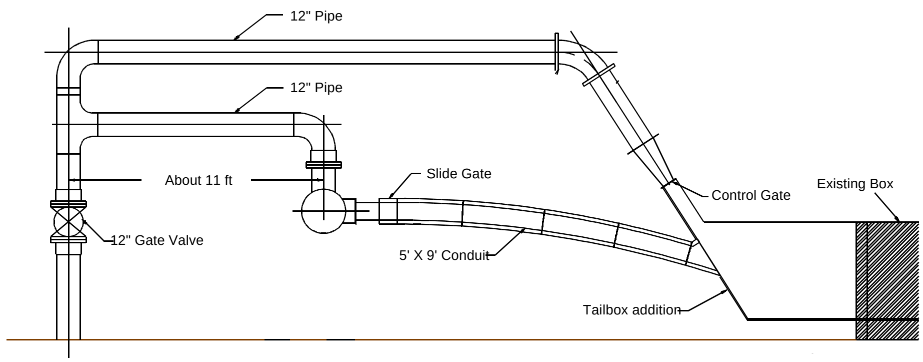


Figure 6: Elevation of the 1:12 scale hydraulic sectional model.

The model similitude was based on equating the Froude numbers of the model and the prototype:

$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}} \qquad (1)$$

where: V = velocity
L = length
g = gravitational acceleration
m = model
p = prototype

This lead to the following scale relationships when a common fluid (water) is used in both model and prototype: $L_p=12L_m$, $V_p=3.464V_m$, *and* $Q_p=498.83Q_m$. The scale was chosen due to the desire to measure air demand characteristics. Model Reynolds Numbers ranged from $1.5X10^5$ to $2X10^5$. Prior research has shown that to model free surface flows with air entrainment, the flows in the model need to be fully turbulent, $\boldsymbol{Re}_m \geq 10^5$ [Wood, 1991]. Much of the prior defining work was done on spillway aerators, a similar concept to the modifications which were tested in this gate model.

Data were collected for a range of reservoir elevations and gate openings. At each point, water discharge was measured using venturi meters. The venturi meters were calibrated against a weigh tank and provide discharge accuracy to within 0.1-percent. Pressures along the conduit invert downstream from the regulating gate were measured using piezometers with water manometers. Piezometer taps were located along the centerline of the invert of the 5- by 9-ft conduit at 9.25, 11.5, 12.5, 16.5, and 22.5 ft downstream from the regulating gate. The amount of air flowing into the conduit downstream from the regulating gate was measured using an orifice plate with three different sized orifices. Multiple orifice plates were used in order to simulate various loss coefficients in the vent/manifold system, including K=1.55, K=6.91, and K=28.85.

Calculations based on Isbester's study showed the air vent system to be well undersized. The 5-ft-diameter air intake header would not be able to carry the full capacity with all gates operating. In addition to increasing the air vent capacity, a more effective method to distribute the air to the sidewalls and invert downstream from the gates was needed. Previous studies on aeration slots and ramps [Beichley 1975, Beichley and King 1975, Pinto, et.al. 1984, Volkart and Rutschmann 1986] have shown them to be effective in reducing the potential for cavitation damage in outlet works and on spillways. The addition of even small quantities of air into the flow along boundaries has proven effective in eliminating cavitation damage [Peterka, 1953].

The model was first used to verify data for the as-built condition. Once this was completed, an insert resembling the constriction in a jet-flow gate was installed and tested. The 6-inch-high ramp angled at 45-degrees yielded a large reduction in discharge capacity (20- to 25-percent) and was abandoned in favor of reduced slope, smaller offset ramps. Three different aeration ramp configurations were tested. These ramps were placed just downstream from the regulating gate. All ramps had a 15-in horizontal length, yielding offsets of 3 in and 1.5 in for the 1:5 and 1:10 ramps respectively. The modifications which were tested are shown in figure 7. These ramps were designed to allow air from the present vent system to be distributed down the sidewalls and along the conduit floor.

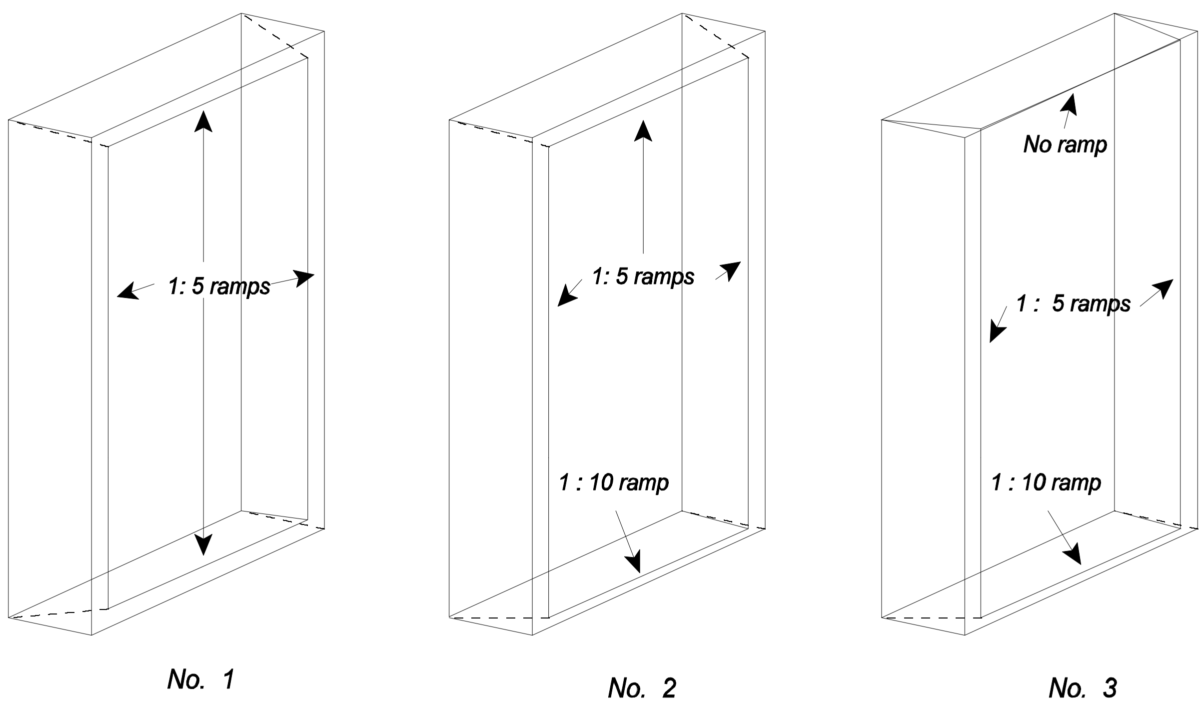


Figure 7: Ramp configurations tested in the hydraulic scale model.

Results

Model experiments began with measurements of the original as-built conditions. Discharge characteristics along with air demand and pressures downstream from the gate were measured. Figure 8 shows the as-built discharge for one lower-level outlet conduit. Results from three reservoir elevations ranging from 400 ft to 450 ft are reported. The air demand is shown on figure 9, results are reported for a vent/manifold loss factor, K=6.91. Piezometric pressures downstream from the gate are reported in figure 10.

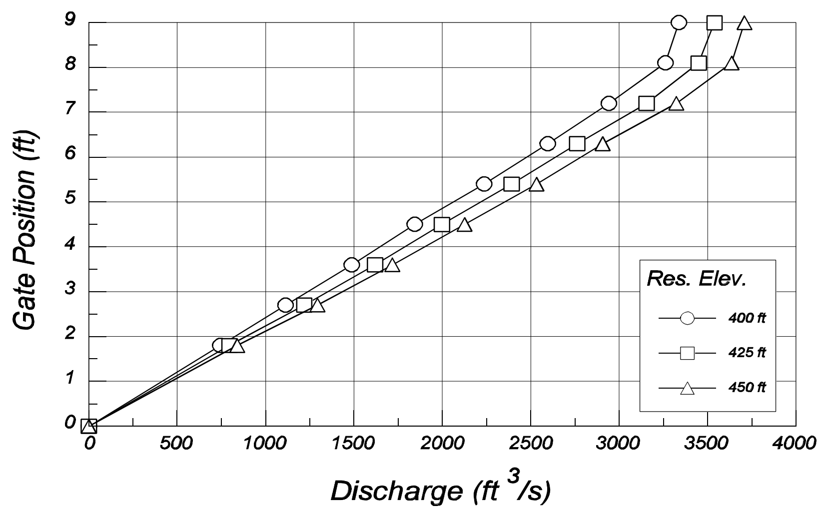


Figure 8: Discharge for one, low-level outlet conduit, as-built conditions.

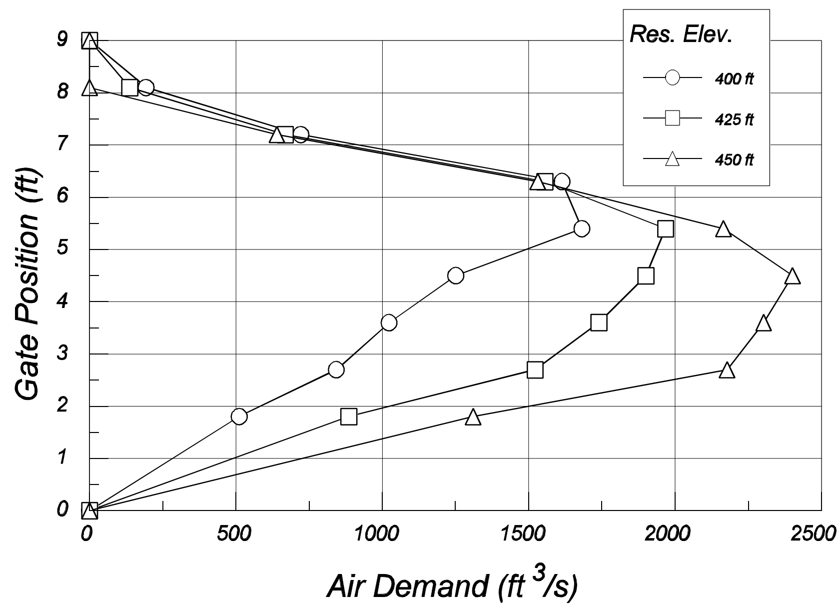


Figure 9: Air demand for a low-level outlet conduit, as-built conditions.

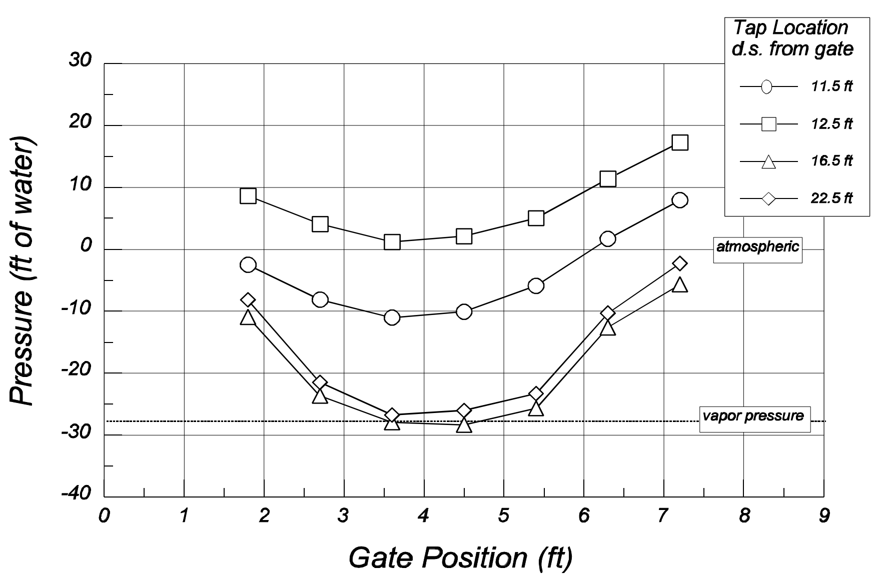


Figure 10: Pressures on the conduit invert, downstream from the regulating gate. Reservoir elevation 450 ft.

The third and final insert that was tested featured no upper ramp. The side ramps remained at a 1:5 slope and the bottom ramp was at 1:10, figure 7. The data reported for this insert were taken at range of reservoir elevations from 400- to 450-ft, and an air vent loss coefficient of K=6.91. The discharge with insert No. 3 in place appears in figure 11. The air demand and piezometric pressures downstream from the gate are shown in figures 12 and 13 respectively.

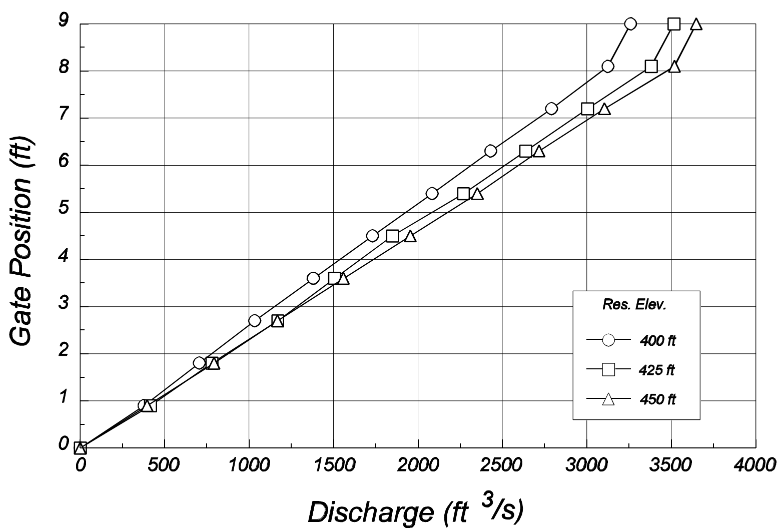


Figure 11: Discharge for one low-level outlet conduit with Insert No. 3 installed.

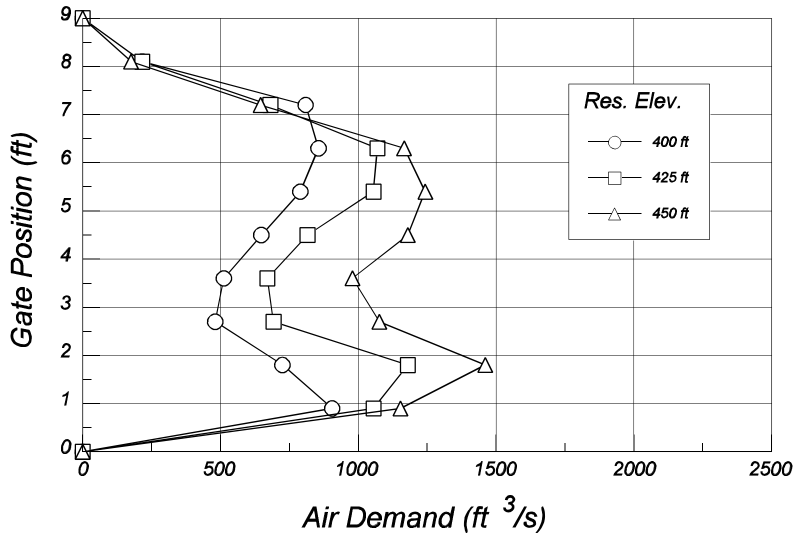


Figure 12: Air demand for one low-level outlet conduit with with Insert No. 3 installed.

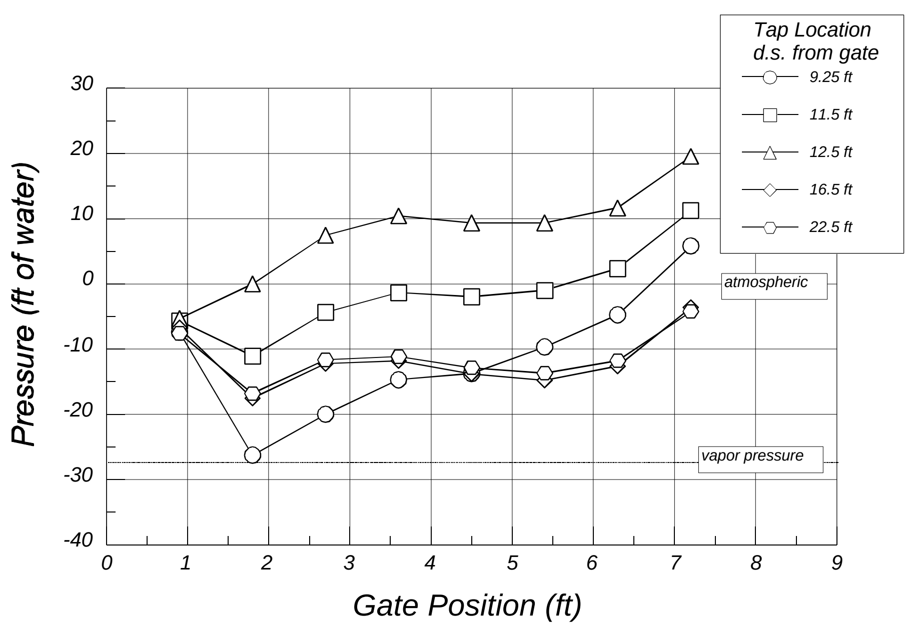


Figure 13: Piezometric pressures downstream of the regulating gate with Insert No. 3 in place.

Discussion

Historically, the outlet works at Folsom Dam have operated infrequently. Modified operations, construction activities, and large storm events are primarily responsible for the flows that resulted in cavitation damage to the outlet conduits in 1997. In addition, an undersized air manifold that distributes air just downstream from each of the eight regulating gates appears to be responsible for air starvation of specific conduits, resulting in variable amounts of damage.

Analysis of the cavitation potential for the mean flow shows a cavitation index greater than 0.2; where the cavitation index is given by:

$$\sigma = \frac{P_o - P_v}{\rho V_o^2/2} \qquad (2)$$

where: P_o = reference pressure and P_v = vapor pressure
V_o = reference velocity
ρ = density of water

Usually no damage occurs at $\sigma \geq 0.2$ [Falvey, 1990]. However, localized flow features such as vortices, can still carry a vapor core and cause damage during collapse and implosion of the vortex core. The damage patterns which have occurred in the Folsom outlets show characteristics of damage resulting from shear layers or vortices emanating from the gates or gate slots.

Air demands measured for the as-built condition (no ramps) showed a substantial air flow into the conduit behind the gate. At a reservoir elevation of 450 ft, a maximum demand of 2400 ft^3/s was measured for a single low-level outlet. The corresponding demand for an upper-level outlet would be about 1600 ft^3/s. Using these data, a total air flow requirement if all eight gates were operating at a reservoir elevation of 450 ft, would be about 16,000 ft^3/s of air. With the present 5-ft-diameter air header, velocities would easily exceed the design limitations of maintaining subsonic flow.

Solving the damage problem appears to be two-fold; an increase in the capacity of the air manifold that supplies air to the regulating gates is needed, as well as a method to better distribute the air to the locations which need it, i.e. the invert and side walls just downstream from the gates.

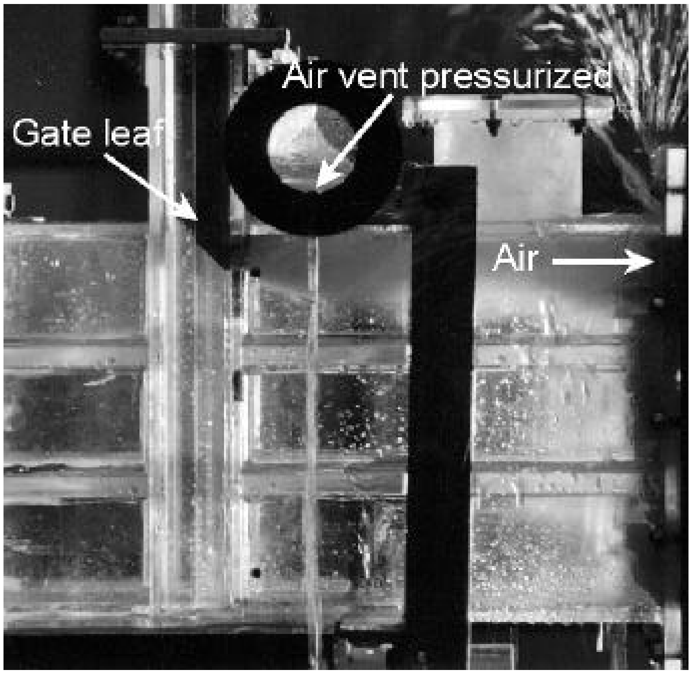
Previous and present model studies reinforced the fact that the current air header (5-ft-diameter) is well undersized, restricting the quantities of air which are distributed to each of the eight outlet gates. A new air intake was designed and constructed at Folsom Dam. This intake was sized based on trying to limit air velocities in the vent to 100 ft/s. In addition, the size was increased slightly to facilitate construction. The new vent was drilled-and-blasted from the left abutment and joined with the existing 5-ft-diameter air header. The system was then split by installation of a bulkhead, allowing four outlet gates to be supplied by the existing system, and four gates to be supplied by the new air intake.

The introduction of air into an area where cavitation damage potential exists can be an effective way to lessen or eliminate possible damage which might result. A standard method developed over the years is to separate the flow from the boundary and allow air to be pulled to the area naturally, by the low pressures created by the separation. This method has been used on many spillway applications and while it has not seen wide application on outlet works, it has also been effective.

The effectiveness of an aeration ramp is not strictly evaluated on the amount of air which is pulled into the vent. Of more concern is how well the air is distributed along the sidewalls and invert areas of the structure in question. Even though the as-built condition has a large air demand, most of the air just passes down the conduit along the top of the water flow without mixing effectively. This is due to the very rough water surface and large amounts of spray generated by the gate operation. A properly designed aeration ramp or slot can effectively distribute air to regions of the conduit which needs protection. Figure 14 and 15 show model photos comparing the as-built with Insert No. 3.

Insert No. 3 performed well throughout the testing and was chosen as the final design to be installed in the prototype. This insert can be welded to the existing steel liner, allowing for easy installation. The insert reduces the flow area by 11.25-percent at the point of the largest constriction, however a discharge reduction of only 2- to 3-percent was measured.

With the combination of the new aeration ramp and construction of an additional air intake manifold (over doubling the capacity), operation of the outlet works should be possible without any additional cavitation damage.



a) Gate position is 90%, head is 450 ft, as-built. Air vent is pressurized (note stream of water pouring out of air vent.

b) Gate position is 90%, head is 450 ft, final design aeration ramp installed just downstream from the gate slot. Note air vent is not pressurized and air is being carried all the way to the floor.

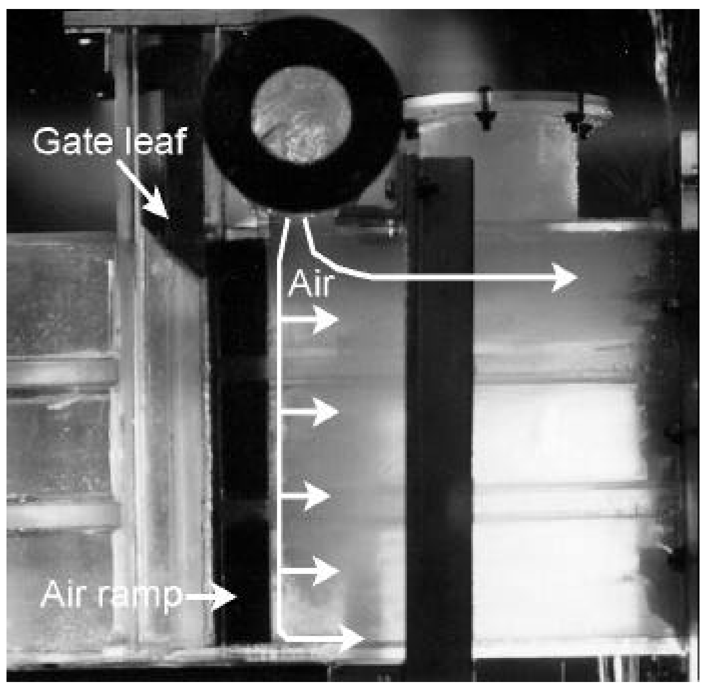
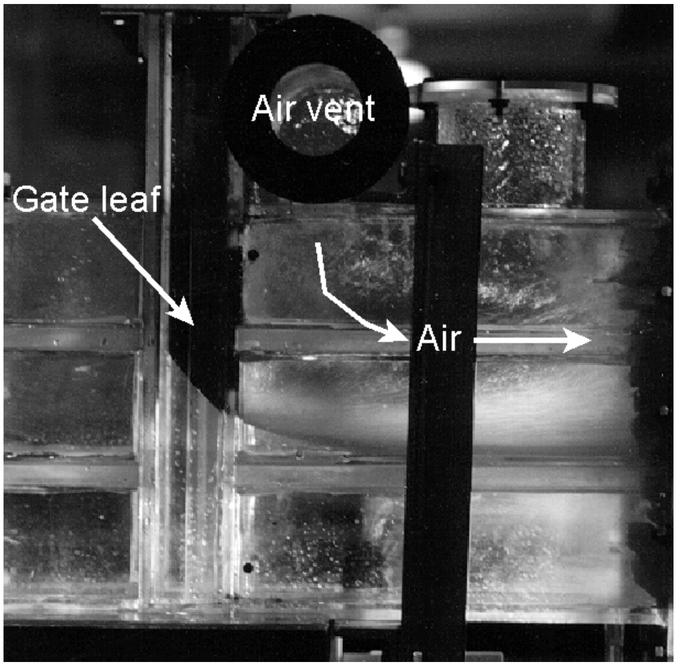
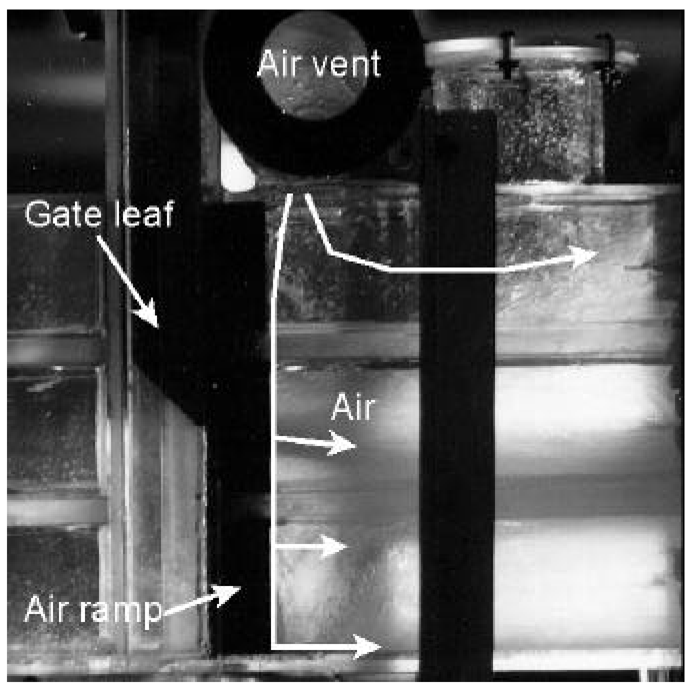


Figure 14: Comparison of as-built and final design for a gate opening of 90% at a head of 450 ft.



a) Gate position 50%, head 450 ft, as-built configuration. Note that aeration appears to be localized at the free surface.



b) Gate position 50%, head is 450 ft. Insert No. 3 aeration ramp installed, note that air is carried down to the conduit floor, allowing for aeration over the entire fluid stream.

Figure 15: Comparison of the as-built configuration with the final design aeration ramp. Gate position is 50-percent (4.5 ft open) at a head of 450 ft.

References

Beichley, G.L. and D.L. King. 1975. “Cavitation Control by Aeration of High-velocity Jets,” *Journal of the Hydraulics Division, ASCE,* Vol. 101, No. HY7, pp.829-846.

Falvey, Henry T. 1990. *Cavitation in Chutes and Spillways,* Engineering Monograph No. 42, Bureau of Reclamation, Denver, CO.

Isbester, T.J. 1971. Hydraulic Model Studies of the Folsom Spillway-Outlet Junction, REC-ERC-71-12, Bureau of Reclamation, Denver, CO.

Peterka, A.J. 1953. “The Effect of Entrained Air on Cavitation Pitting,” Proceedings of the Joint Meeting of the International Association for Hydraulic Research and the American Society of Civil Engineers, Minneapolis, MN.

Pinto, N.L. de S., S.H. Neidert, and J.J. Ota. 1982. “Prototype and laboratory experiments on aeration at high velocity flows,” *Report No. 36,* Centro de Hydraulica e Hidrologia Prof. Parigot de Souza, Universidade Federal do Parana, Curitiba, Brazil.

U.S. Army Corps of Engineers. 1965. “Spillway and Sluices, Red Rock Dam, Des Moines River, Iowa,” Technical Report No. 2-673, Waterways Experiment Station, Vicksburg, MS.

Volkart, P. and P. Rutschmann. 1986. “Aerators on Spillway Chutes: Fundamentals and Application,” *Proceedings of the ASCE Specialty Conference on Advancements in Aerodynamics, Fluid Mechanics, and Hydraulics,* Minneapolis, MN.

Wood, I.R. (Editor) 1991. *Air Entrainment in Free-Surface Flows,* International Association for Hydraulic Research, Hydraulic Structures Design Manual 4, A.A. Balkema, Rotterdam, Netherlands.